

PATENT APPLICATION

TRANSMITTER FOR LOW VOLTAGE DIFFERENTIAL SIGNALING

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TRANSMITTER FOR LOW VOLTAGE DIFFERENTIAL SIGNALING

FIELD OF THE INVENTION

[0001] The present invention is related to output drivers, and in particular to output drivers
5 operative using low voltage differential signaling.

BACKGROUND OF THE INVENTION

[0002] In the communications field, there is a constant need to transmit larger amounts of
digital data in shorter time intervals. In accordance with one method that is gaining increasing
10 acceptance, data is transmitted over high-speed serial buses. These buses often carry digital
data serially over a pair of conductors, driven either in a single-ended form or differentially.
The differential drive method offers advantages over the single-ended drive method. The
noise immunity of the differential method is greater than that of a comparable single-ended
method. The improved noise immunity allows the use of lower signal amplitudes on the
15 differential bus compared to the single-ended bus. Lower signal amplitudes often enable
higher data transmission rates and lower overall power consumption.

[0003] One conventional standard for differential data transmission is referred to as the low
voltage differential signaling (LVDS) standard, defined in "TIA/EIA-644, revision A,
Electrical Characteristic of Low Voltage Differential Signaling (LVDS) Interface Circuits"
20 and "ANSI/TIA/EIA-644, revision A, January 30, 2001" published by Telecommunications
Industry Association. This standard defines a differential data bus with a recommended
maximum data signaling rate of 655 million bits per second on up to 5 meters of wire cable.
The standard also requires that the generator, or transmitter, be able to generate a differential
voltage signal in the range of 250 mV to 450 mV across a resistive load having a resistance of
25 100 Ω . The midpoint of the differential output voltage is defined as the offset voltage and is
required to be between 1125 mV and 1375 mV.

[0004] Fig. 1 shows a known differential output driver 80 that conforms to the LVDS
standard and is described in the US Patent No. 6,111,431. In Fig. 1, mimicking circuit MC
generates two reference voltages at nodes ND1 and ND6. The voltage at node ND1 is
30 replicated in node ND2 using operational amplifier OPAMP1 and PMOS transistor P2 of the
driver circuit DC. Operational amplifier OPAMP1 and transistor P2 together form a voltage

buffer. Similarly, the voltage at node ND6 is replicated in node COM using operational amplifier OPAMP2 and NMOS transistor N1 of the driver circuit DC. Operational amplifier OPAMP2 and transistor N1 together form a voltage buffer. Transistors N21, N22, N23 and N24 form an H-bridge and are used as switches. Load resistor R_L is connected between nodes A and B of the H-bridge. Since the input signals IN and INB are complements of each other, depending on the polarity of these input signals, current I_2 flows from the H-bridge to transistor N1 either through the path defined by transistor N21, resistor R_L , and transistor N24, or through the path defined by transistor N22, resistor R_L , and transistor N23. The reference voltage levels are generated in MC such that when these voltages are replicated at nodes ND2 and COM, the resulting output voltage across resistor R_L conforms to the LVDS standards.

BRIEF SUMMARY OF THE INVENTION

[0005] In accordance with the present invention, a low-voltage differential signal driver includes, in part, a current sourcing circuit, a current steering circuit, and a current sinking circuit. The current steering circuit steers the current generated by the current sourcing circuit in a first direction to generate a positive differential output voltage or in a second direction to generate a negative differential output voltage. The steered current flows to the ground via the current sinking circuit. The low-voltage differential signal driver further includes, in part, a voltage dividing circuit, a first voltage regulating circuit and a second voltage regulating circuit. The voltage dividing circuit divides the generated output voltage. The first voltage regulating circuit receives a first reference voltage and regulates the voltage of the node coupling the current steering circuit and the current sinking circuit. The second voltage regulating circuit receives a first supply voltage to regulate the voltage of the node carrying the divided output voltage.

[0006] In one embodiment, the first voltage regulating circuit includes a first operational amplifier whose output voltage is applied to the gate terminal of an MOS transistor disposed in the current sinking circuit. Similarly, the second voltage regulating circuit includes a second operational amplifier whose output voltage is applied to the gate terminal of an MOS transistor disposed in the current sourcing circuit. To track the on-resistance of the transistors disposed in the current steering circuitry, the low-voltage differential signal driver further includes, in part, a replicating circuit that receives the first supply voltage and, in response, generates the first reference voltage that is applied to the first operational amplifier.

[0007] To ensure that the currents flowing to the output terminals of the low-voltage differential signal driver do not exceed predefined values, a first current limiting circuitry is coupled between the current sourcing circuit and a second voltage supply, and a second current limiting circuitry is coupled between the current sinking circuit and the ground terminal. A tri-state output circuit that is coupled to the current steering circuit, tri-states the voltage signals present on the output terminals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Fig. 1 is a schematic diagram of a low-voltage differential signal driver, as known in the prior art.

[0009] Fig. 2 is a schematic diagram of a low-voltage differential signal driver, in accordance with one embodiment of the present invention.

[0010] Fig. 3 is a schematic diagram of a replicating circuit adapted to supply a reference voltage to the low-voltage differential signal driver of Fig. 2.

[0011] Fig. 4 shows the low-voltage differential signal driver of Fig. 2 coupled to the replicating circuit of Fig. 3.

[0012] Fig. 5 is a schematic diagram of a low-voltage differential signal driver, in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0013] Fig. 2 is a schematic diagram of a low-voltage differential signaling (LVDS) output driver circuit 100, in accordance with one embodiment of the present invention. LVDS output driver circuit (hereinafter alternatively referred to as output driver) 100 uses a reference voltage and a pair of complementary control signals to generate output voltages at terminals A and B and that are compatible with the TIA/EIA-644-A standard.

[0014] Disposed, in part, in output driver 100 is an H-bridge current steering circuit 102, that includes NMOS transistor switches 4, 6, 8 and 10, a current sourcing circuit that includes NMOS transistor 2, and a current sinking circuit that includes PMOS transistor 12. Resistor R_L coupled between terminals A and B represents the resistive load and is external to output driver 100. Output driver 100 further includes, in part, two control loops. The first control loop includes operational transconductance amplifier (OTA) 22 and PMOS transistor 12. The

second control loop includes OTA 20, NMOS transistor 2, and a voltage dividing circuit 24 that, in combination, provide a common-mode feedback network. Voltage dividing circuit 24, in turn, includes resistors 14, 16 and capacitor 18.

[0015] Transistors 4, 6, 8 and 10 (these transistors are hereinafter alternatively referred to as switches) of the H-bridge 102 are controlled by input signals D and DB that have complementary rail-to-rail voltage levels. Therefore, each of input signals D and DB is either at a high or a low logic level. Input signal D is applied to the gate terminals of NMOS transistors 4 and 10, and input signal DB is applied to the gate terminals of NMOS transistors 6 and 8. Input signals D and DB steer current I_O generated by NMOS transistor 2 through the load resistor R_L before this current is delivered to the ground terminal via PMOS transistor 12. Depending on the polarity of the input signals, either a positive voltage $+V_{OP}$ or a negative voltage $-V_{OP}$ voltage is developed across load resistor R_L .

[0016] For simplicity, in the following each of switches 4, 6, 8, 10 is assumed to be an ideal switch. Therefore, each of these switches is assumed to have an on-resistance of zero and an off-resistance of infinity. To develop a positive voltage $+V_{OP}$ across load resistor R_L , signal D is supplied with a relatively high voltage level and signal DB is supplied with a relatively low voltage level. Therefore, switches 4 and 10 are on (i.e., conducting state), whereas switches 6 and 8 are off (non-conducting state). Accordingly, current I_O flows from current sourcing NMOS transistor 2 to the ground terminal via switch 4, load resistor R_L , switch 10 and current-sinking PMOS transistor 12. Because under these conditions, switches 4 and 10 are in conducting states and switches 6 and 8 are in non-conducting states and each of these switches is assumed to be an ideal switch, terminal A is at the same voltage level (V_{OH}) as node N5, and terminal B is at the same voltage level (V_{OL}) as node N10.

[0017] Resistors 16 and 18 of the voltage dividing circuit 24 have substantially the same resistance, therefore, the voltage V_{CM} at node N15 is approximately equal to the average value of the voltage levels at terminals A and B. In other words, voltage V_{CM} is the average of voltages V_{OH} and V_{OL} . Because resistors 14 and 16 are selected so as to have relatively high resistance values compared to resistor R_L , substantially all of I_O is assumed to flow through resistor R_L .

[0018] Similarly, to develop a negative voltage $-V_{OP}$ across load resistor R_L , signal D is supplied with a relatively low voltage level and signal DB is supplied with a relatively high voltage level. Therefore, switches 4 and 10 are in non-conducting state, whereas switches 6

and 8 are in conducting states. Accordingly, current I_O flows from current-sourcing NMOS transistor 2 to the ground terminal via switch 6, load resistor R_L , switch 8 and current-sinking PMOS transistor 12. Because under these conditions, switches 4 and 10 are in non-conducting states and switches 6 and 8 are in conducting states, terminal A is at the same voltage level as node N10, and terminal B is at the same voltage level as node N5. Because of the symmetry of operation with respect to the polarity of the input signals, node N15 is at the same voltage level V_{CM} . Filter capacitor 18 filters out the transient voltage signals that may develop at node N15 when input signals D and DB make low-to-high or high-to-low transitions.

[0019] The output common mode offset voltage signal V_{OS} and the differential output voltage signal V_{OD} of output driver 100 are defined as below:

$$V_{OD} = V_{OH} - V_{OL} \quad (1)$$

$$V_{OS} = \frac{V_{OH} + V_{OL}}{2} \quad (2)$$

The TIA/EIA-644-A standard requires signal V_{OS} to be between 1125mV and 1375mV, and signal V_{OD} to be between 250mV and 450mV.

[0020] In accordance with the present invention, voltage signal V_{OL} tracks voltage signal V_{ROL} , and therefore voltage signal V_{OL} is regulated to be equal to the voltage signal V_{ROL} . Similarly, voltage signal V_{OS} tracks reference voltage V_{ROS} , and therefore voltage signal V_{OS} is regulated to be equal to the voltage signal V_{ROS} . Voltage signal V_{OL} is regulated using a first voltage regulating circuit formed by OTA 22 and PMOS transistor 12, which in combination also form a first control loop. Similarly, voltage signal V_{OS} is regulated using a second voltage regulating circuit formed by OTA 20, NMOS transistor 2, and voltage dividing circuit 24, which in combination also form a second control loop.

[0021] The non-inverting input terminal of OTA 22 receives voltage V_{ROL} and the inverting input terminal of OTA 22 is coupled to node N10. If the voltage at node N10 falls below V_{ROL} , OTA 22 increases the voltage applied to the gate terminal of PMOS transistor 12, thereby causing PMOS transistor 12 (i.e., current sinking circuit 12) to become less conductive and thus lowering the current that flows through PMOS transistor 12. This causes the voltage at node N10 to increase and cancel out the factors that caused the voltage at node

N10 to fall below V_{ROL} . Similarly, when the voltage at node N10 raises above V_{ROL} , OTA 22 decreases the voltage applied to the gate terminal of PMOS transistor 12, thereby causing PMOS transistor 12 to become more conductive and thus increasing the current that flows through PMOS transistor 12. This causes the voltage at node N10 to decrease and cancel out the factors that caused the voltage at node N10 to raise above V_{ROL} . Accordingly, this feed-back loop regulates and maintains the voltage V_{OL} of node N10 at a voltage level substantially equal to the reference voltage V_{ROL} .

[0022] The non-inverting input terminal of OTA 20 receives voltage signal V_{ROS} and its inverting input terminal is coupled to node N15. If the voltage at node N15 falls below V_{ROS} , OTA 22 increases the voltage applied to the gate terminal of NMOS transistor 2 (i.e., current-sourcing NMOS transistor 2), thereby causing NMOS transistor 2 to become more conductive and thus increasing the current that flows through NMOS transistor 2. This causes the voltage at node N15 to increase and cancel out the factors that caused the voltage at node N15 to fall below V_{ROS} . Similarly, if the voltage at node N15 increases above V_{ROS} , OTA 22 decreases the voltage applied to the gate terminal of NMOS transistor 2, thereby causing NMOS transistor 2 to become less conductive and thus decreasing the current that flows through NMOS transistor 2. This causes the voltage at node N15 to decrease and cancel out the factors that caused the voltage at node N15 to increase above V_{ROS} . Accordingly, this feed-back loop regulates and maintains the voltage V_{CM} of node N15 at a voltage level substantially equal to the reference voltage V_{ROS} .

[0023] Since voltage V_{CM} is the average of the voltages V_{OL} and V_{OH} , voltages V_{CM} and V_{OS} --defined in the above equation (2)--are substantially the same. Consequently, the second control loop regulates voltage V_{OS} at a level that is substantially equal to the level of the voltage V_{ROS} . Furthermore, differential output voltage V_{OD} and the common-mode offset voltage V_{OS} may also be defined in terms of the applied reference voltages V_{ROL} and V_{ROS} , as shown below:

$$V_{OD} = 2 \times (V_{ROS} - V_{ROL}) \quad (3)$$

$$V_{OS} = V_{ROS} \quad (4)$$

Applied reference voltage V_{ROS} is typically selected to have a value of, e.g., 1250mV (i.e., the mid point of voltage levels 1125mV to 1375mV specified by the TIA/EIA-644-A standard) to allow for variations in, e.g., process, voltage and temperature. In accordance with equation (3), voltage V_{ROL} is set to, for example, 1075mV, so as to provide a typical value of 350mV for voltage V_{OD} .

[0024] As described above, each of transistor 4, 6, 8, 10 has a non-ideal switching characteristic. This non-ideal switching characteristic causes a voltage drop across each of these transistors when that transistor is in a conducting state. Such a voltage drop may reduce the differential output swing below the specification limits. One method for compensating for this voltage drop is to decrease the reference voltage V_{ROL} by an amount representative of such a voltage drop, thereby causing the voltage V_{OD} to fall within the required limits, as described further below.

[0025] Fig. 3 shows the schematic diagram of an LVDS output replication circuit 200, in accordance with the present invention, adapted to compensate for the voltage drop resulting from the non-ideal switching characteristics of transistors 4, 6, 8, 10. As seen from Fig. 3, LVDS output replication circuit 200 (hereinafter alternatively referred to as replication circuit 200) receives first supply voltage V_{ROS} , and in response, generates output signal V_{ROL} via a control loop that includes PMOS transistor 32, OTA 34, DC current source 26, resistor 28, and NMOS transistor 30.

[0026] Concurrent references are made to Figs. 2 and 3 below. Resistor 28 of replication circuit 200 replicates (i.e., mimics) half of load resistor R_L of Fig. 2. NMOS transistor 30 replicates either of NMOS transistor 8 and 10, whichever is in a conducting state. DC current source 26 replicates current I_O flowing through NMOS transistor 2. In order to minimize the power consumption, the transistors and resistor in replication circuit 200 are selected so as to operate at a current level of I_O/M , where M is a positive number greater than unity. Thus, replica resistor 28 of Fig. 3 is selected to have a resistance of $M \cdot R_L/2$. Similarly, the ratio of the channel-width to channel-length $(W/L)_{30}$ of replica NMOS transistor 30 of Fig. 3 is selected so as to be equal to $(W/L)_s/M$, where $(W/L)_s$ is the ratio of the channel-width to channel-length of the replicated NMOS transistors 8 and 10. Since transistor 30 is adapted to replicate either transistor 8 or transistor 10 when it is in a conducting state, the gate terminal of transistor 30 is coupled to the positive voltage supply terminal. Replica PMOS transistor 32 replicates PMOS transistor 12 of Fig. 2. Accordingly, the ratio of the channel-width to channel-length $(W/L)_{32}$ of replica PMOS transistor 32 of Fig. 3 is selected so as to be equal

to $(W/L)_{12}/M$, where $(W/L)_{12}$ is the ratio of the channel-width to channel-length of the replicated PMOS transistor 12.

[0027] Voltage supply signal V_{ROS} is applied to the non-inverting input terminal of OTA 34. If the voltage level at node N20 falls below V_{ROS} , OTA 34 increases the voltage applied to the gate terminal of PMOS transistor 32. This causes PMOS transistor 32 to become less conductive, thereby increasing the voltage at node N20. Similarly, when the voltage at node N20 raises above V_{ROS} , OTA 34 decreases the voltage applied to the gate terminal of PMOS transistor 32, thereby decreasing the voltage at node N20. Thus, the voltage at node N20 is regulated and maintained at a level substantially equal to voltage V_{ROS} . As shown in equation (4), voltage V_{ROS} is also substantially equal to the output offset voltage V_{OS} .

[0028] Since the current flowing through replica current source 26 is equal to I_O/M (I_O is the current that flows through NMOS transistor 2 shown in Fig. 2), the voltage drop across resistor 28 of output replica 200 is half of the voltage drop across load resistor R_L . Similarly, the voltage drop across replica NMOS transistor 30 is equal to the voltage drop across either NMOS transistor 8 or 10, whichever is conducting. Voltage V_{ROL} generated by replication circuit 200 thus includes an offset voltage that is substantially equal to the voltage drop across NMOS transistors 8, 10 when they are in conducting states. Therefore, voltage V_{ROL} accounts for the effect of non-zero on-resistances of transistors 4, 6, 8, 10 on the output differential voltage V_{OD} .

[0029] Fig. 4 shows a schematic diagram of LVDS transmitter circuit 300 that is formed by coupling replication circuit 200 to LVDS output driver circuit 100. As seen from Fig. 4, LVDS transmitter 300 receives, in part, voltage supply V_{dd} that supplies a voltage to, e.g., NMOS transistor 2, and voltage supply V_{ROS} that supplies a voltage to the non-inverting input terminals of OTAs 20 and 34. Output voltages generated and delivered to output terminals A and B comply with the TIA/EIA-644-A. The voltage applied to the non-inverting input terminal of OTA 22 is supplied by replication circuit 200.

[0030] Fig. 5 shows the schematic diagram of an LVDS transmitter 600, in accordance with another embodiment of the present invention. LVDS transmitter 600 includes, in addition to the components disposed in LVDS 300 of Fig. 4, a negative current limiting circuitry 70, a positive current limiting circuitry 72, output tri-state circuitry 68, transistors 54 and 56, AND gates 76, 78 and inverter 74.

[0031] Negative current limiting circuitry 70 includes a current sense resistor 38, a pull-down resistor 44, an NMOS transistor 42 and a PMOS transistor 40. Negative current limiting circuitry 70 inhibits high levels of current flow to terminals A or B under certain fault conditions. One such condition occurs when terminals A or B are short-circuited to the ground terminal. Under normal operating conditions, the voltage drop across resistor 38 is less than the threshold voltage of PMOS transistor 40. Thus, no current flows through PMOS transistor 40 or pull-down resistor 44. As a result, the voltage at the gate terminal of NMOS transistor 42 is pulled down to ground potential via resistor 44.

[0032] If a fault condition occurs, e.g., a short-circuit occurs between one or both output terminals A, B and the ground terminal, the current through NMOS transistor 2 increases beyond its normal operating range. The increase in this current causes the voltage across resistor 38 to increase, thereby turning on PMOS transistor 40. Therefore, current flows through PMOS transistor 40 and resistor 44. The resulting voltage drop across resistor 44 turns on NMOS transistor 42. Therefore, the gate-to-source voltage of NMOS transistor 2 is reduced to a level that limits the current through NMOS transistor 2 to a safe level. The resistances of resistors 38 and 44 and the channel dimensions of PMOS transistor 40 and NMOS transistor 42 are selected such that the required current limit is achieved.

[0033] Positive current limit circuitry 72 includes a current sense resistor 52, a pull-up resistor 46, a PMOS transistor 48 and an NMOS transistor 50. Positive current limit circuitry 72 inhibits high levels of currents flow to terminals A or B under certain fault conditions. One such condition occurs when terminals A or B are short-circuited to the positive supply terminal. Under normal operating current conditions, the voltage drop across resistor 52 is less than the threshold voltage of NMOS transistor 50. Thus, no current flows through the NMOS transistor 50 or pull-up resistor 46. As a result, the voltage at the gate terminal of PMOS transistor 48 is raised to the positive supply potential via pull-up resistor 46.

[0034] If a fault condition, e.g., a short-circuit occurs between one or both output terminals A, B and the positive supply terminal, the current through PMOS transistor 12 increases beyond its normal operating range. The increase in this current causes the voltage drop across resistor 52 to increase, thereby turning on NMOS transistor 50. Therefore, current flows through NMOS transistor 50 and resistor 46. The resulting voltage drop across resistor 46 turns on PMOS transistor 48. Therefore, the gate-to-source voltage of PMOS transistor 12 is reduced to a level that limits the current flow through PMOS transistor 12 to a safe level.

The resistances of resistors 46 and 52 and the channel dimensions of PMOS transistor 48 and NMOS transistor 50 are selected such that the required current limit is achieved.

[0035] In some applications, two or more LVDS output drivers may be coupled to the differential data bus. In these applications, it is required to selectively disable (i.e., tri-state) the output signals of all but one of the LVDS drivers. The data from the non-disabled driver is delivered to the bus for transmission. Transistors 58, 64 and resistors 60, 62 shown within the dashed perimeter line 68, in combination with NMOS transistors 54 and 56, AND gates 76 and 78 and inverter 74 form a tri-state output circuit that enables or disables the delivery of output signals to terminals A and B, as described further below.

[0036] When signal EN is at a high level, signal D is delivered to NMOS transistors 4, 10 via AND gate 76, and signal DB is delivered to NMOS transistors 6, 8, via AND gate 78. Similarly, NMOS transistors 54 and 56 are both conducting, thus coupling voltage dividing circuit 24 to terminals A and B. Furthermore, because signal DIS is at a low level, NMOS transistors 58 and 64 are turned off, therefore, transistors 58, 64 and resistors 60, 62 are decoupled from LVDS output driver 500. Accordingly, when signal EN is at a high level, LVDS output driver 500 is enabled and operates in the normal mode, as described in detail above. The on-resistance of each of NMOS transistors 54 and 56 is selected to be lower than the resistance of resistors 14 and 16. Therefore, the effect of the on-resistance of NMOS transistors 54 and 56 on the operation described above is negligible.

[0037] In order to tri-state the output signals, i.e., force the output signals to a high-impedance state, signal EN is set to a low level, thereby turning off NMOS transistors 4, 6, 8 and 10. Similarly, because signal EN is at a low level, both NMOS transistors 54 and 56 are also off, thereby decoupling voltage dividing circuit 24 from the terminals A and B, which in turn, breaks the feedback path of the control loop formed by OTA 20 and NMOS transistor 2.

[0038] To prevent node N5 from having an undefined voltage level when terminals A and B are tri-stated, circuitry 68 provides a feedback loop supplying the voltage present at the common terminal of resistors 60 and 62 to the inverting input terminal of OTA 20. This feedback loop further ensures that differential output voltage between terminals A and B reaches its value without undergoing excessive delays after signal EN is forced to a high logic level.

[0039] Channel dimensions of NMOS transistors 58 and 64 are selected so as to have a channel-width to channel-length ratio that is equal to $(W/L)_s/K$ where $(W/L)_s$ is the ratio of the channel-width to channel-length of any one of NMOS transistors 4, 6, 8, 10, and K is a

positive number greater than unity. The resistance of each of resistors 60 and 62 is selected to have a value of $K \cdot R_L / 2$ where R_L is the resistance of the external load resistor. Thus, when signal EN is at a low level, NMOS transistors 58 and 64 are turned on, and a current having the size of I_O / K flows through transistor 58, resistor 60, resistor 62, and transistor 64, thereby replicating the operation of one half of the current steering circuit 102. The voltage developed at node N15 is therefore equal to V_{OS} , thereby keeping the value of the voltage signal delivered via the feedback loop constant. This ensures that the voltage at node N5 is kept at substantially the same level, regardless of whether the LVDS driver output signals are enabled or tri-stated (disabled). This also ensures that data transmission may start shortly after the output signals are enabled.

[0040] The above embodiments of the present invention are illustrative and not limitative. The invention is not limited by the type of amplifier used in the low-voltage differential signal driver of the present invention. The invention is not limited by the type of integrated circuit in which the low-voltage differential signal driver of the present invention may be disposed. Nor is the invention limited to any specific type of process technology, e.g., CMOS, Bipolar, or BICMOS, or otherwise that may be used to manufacture the low-voltage differential signal driver of present invention. Other additions, subtractions, deletions, and modifications may be made without departing from the scope of the present disclosure as set forth in the appended claims.